Star formation rates of distant luminous infrared galaxies derived from Hα and IR luminosities[⋆]

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Abstract. We present a study of the star formation rate (SFR) for a sample of 16 distant galaxies detected by ISOCAM at 15μm in the CFRS0300+00 and CFRS1400+52 fields. Their high quality and intermediate resolution VLT/FORS spectra have allowed a proper correction of the Balmer emission lines from the underlying absorption. Extinction estimates using the Hβ/Hγ and the Hα/Hβ Balmer decrement are in excellent agreement, providing a robust measurement of the instantaneous SFR based on the extinction-corrected Hα luminosity. Star formation has also been estimated exploiting the correlations between IR luminosity and those at MIR and radio wavelengths. Our study shows that the relationship between the two SFR estimates follow two distinct regimes: (1) for galaxies with SFR$_{IR}$ below $\sim 100 M_\odot/yr$, the SFR deduced from Hα measurements is a good approximation of the global SFR and (2) for galaxies near of ULIRGs regime, corrected Hα SFR understimated the SFR by a factor of 1.5 to 2. Our analyses suggest that heavily extincted regions completely hidden in optical bands (such as those found in Arp 220) contribute to less than 20% of the global budget of star formation history up to z=1.

Key words. galaxy formation – infrared – star formation rate

1. Introduction

In the last few years, great steps toward a better understanding of the distant Universe have been done using a panchromatic approach. The mid IR windows opened by the camera ISOCAM (Cesarsky et al, 1996) have lead to the identification of the galaxies responsible for the bulk of the infrared background, a population of dusty galaxies which evolves very rapidly in number (Elbaz et al., 1999, 2002). Luminous Infrared Galaxies (LIRGs, $L_{IR} \geq 10^{11} L_\odot$) detected by ISO are mainly dusty starbursts (Fadda et al., 2002) with large star formation ($> 50 - 100 M_\odot/yr$) triggered by interactions, $\sim$30-40% of detected galaxies show optical signs of interaction (Flores et al., 1999). Rigopoulou et al. (2000, hereafter R00) using the VLT studied the near IR spectra of a few LIRGs and claimed that the SFR measured from IR luminosity (hereafter SFR_{IR}) is at least 3 times higher than that based on Hα luminosity (hereafter SFR$_{H\alpha}$). However, this claim is affected by large uncertainties on the SFR$_{H\alpha}$, in absence of a proper extinction correction. Indeed extinction for such heavily dust-shrouded objects is very important, and only accurate estimates of the extinction can confirm or infirm the R00 claim. Recently, Hammer et al. (2001)

have analyzed intermediate resolution VLT/FORS spectra (R=3.5Å at rest) of 3 compact LIRGS at z∼0.6. They derived accurate fluxes for Balmer emission lines (Hβ, Hγ) after a proper removal of the underlying stellar absorption. Extinction estimates using observed Hβ/Hγ ratio were used to correct $H\beta$ luminosities and derive SFR$_{H\alpha}$ which are consistent with SFR_{IR}. These objects present strong metallic and Balmer absorption lines combined with intense emission lines, which indicate a particularly complex star formation history (Hammer et al, 2001). It is unclear yet if these properties are shared by the whole galaxy population at intermediate redshifts. Indeed, at z $\geq$ 0.4, an important fraction of the galaxy population was identified to Balmer-strong galaxies with emission, in the field (Hammer et al, 1997) and in galaxy clusters (Poggianti et al, 1999).

This letter presents a preliminary study of 16 LIRGs out of a sample of 90 observed at VLT and CFHT. The data are described in Section 2. Section 3 summarizes the different techniques used for the data analysis. The determination of the SFR is discussed in Sections 4 and 5. Throughout this paper we adopt H$_0$=50 km/s/Mpc and q$_0$=0.5 ($\Omega_M = 1, \Omega_{Lambda} = 0$).
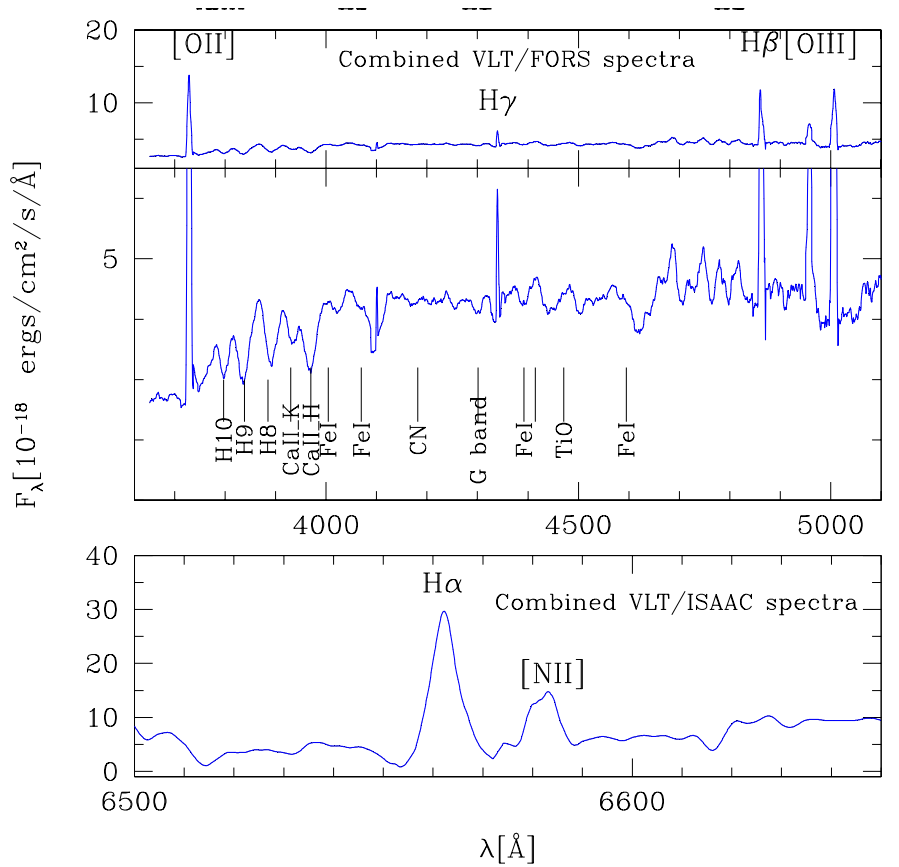

Fig. 1. Combined VLT FORS+ISAAC spectra, after masking sky emission lines, and smoothing the continuum of both galaxies (see Hammer et al. 2001;Gruel et al. in prep). Zooms in the center shows details of our spectra (S/N>5 per resolution element in the continuum), including the underlying Balmer absorption. Lower panel shows combined near IR spectra.

2. Observations and sample selection

Deep MIR data were obtained in a region of 13x13 sq. arcmin centered on the CFRS0300+00 field, using ISOCAM broadband filters LW3 (12-18 μm, centered at 14.3 μm) and LW2 (5-8 μm, centered at 6.75 μm) for a total integration time per sky position of 23 and 15 minutes, respectively. The reduction of IR data was done using the standard method described by Fadda et al (2001), resulting in a catalog of detected sources, which will be published in a subsequent paper.

Among the 40 LIRGs galaxies possessing a redshift (from Canada France Redshift Survey, Hammer et al, 1995) we have randomly selected 14 galaxies which have been observed together using the VLT/FORS2/MXU (runs 66.A-0599(A), 68.A-0298(A)) and 2 additional objects were observed with the CFHT/MOS (run 98IF65A). The 8 distant LIRGs (z> 0.6) were pre-selected to avoid contamination of their near IR redshifted $H\alpha$ line by strong OH sky emissions. The sample is then well representative of LIRGs in the CFRS0300+00 field. Optical VLT observations were done in service mode during periods 66 and 68 using two differents FORS2 set-ups (R600 and I600 grisms, 3 hour each, R~1300) with a slit width of 1.5 arcsec. CFHT data were obtained in two different runs in 1998 and 2000, using standard MOS setup (R300 grism and 1.5 arcsec slit, 4 hrs, R=660). Near IR spectra of four galaxies were collected in runs 66.A-0599(A) and 69.B-0301(A) with the infrared spectrometer VLT/ISAAC. For the near IR observations we used the medium resolution grating $R_s \sim 3000$ and a 2" slit, for a total of 1 hr of integration time nodding along the slit (ABBA configuration). Targets were first acquired using a reference star at a distance of 1', with a 1–2 min exposure in the Js-band. For four objects, we have used VLT/ISAAC archive data (Program 63.O-0270(A)). These galaxies were observed using the same instrumental setup. Data reduction and extraction of optical and near-IR spectra were performed using a set of IRAF procedures developed by our team, which allowed us to reconstruct simultaneously the spectra and the sky counts of the objects.

3. Data analysis procedure

Figure 1 shows the median optical (VLT/FORS) and the near IR VLT spectra (VLT/ISAAC) of the 8 distant

LIRGs. The spectra were flux-calibrated using standard stars for both optical and near IR spectra. Broadband filter images (V to I bands for FORS spectra, J band for ISAAC spectra) were used to compute the spectroscopic aperture corrections. In order to check the validity of the relative aperture corrections, we have produced best fit models of both spectra and photometry using population synthesis models (Bruzual and Charlot, 1993) appropriately corrected for extinction. This procedure has provided an independant test of the spectral calibration and of possible errors in aperture corrections. It results that the uncertainty related to our derived calibration is well below 15%. Underlying Balmer absorption line were estimated after synthetizing the galaxy continuum from 3730Å to 5000Å, including major metallic lines and the high order absorption Balmer lines unaffected by emissions. Synthetic spectra were produced from combinations of 4 stars from B to K type, selected from Jacoby et al (1984), appropriately chose to best fit the continuum and absorption line spectra (see details in Hammer et al, 2001; Gruel PhD thesis, 2002).

4. Extinction and SFR from $H\alpha$, $H\beta$ and $H\gamma$ Balmer emission lines

Median resolution VLT spectra (FORS+ISAAC) allowed us to measure three Balmer emission lines (Hγ, Hβ and Hα) for distant LIRGs. Extinctions were derived from both the Hβ/Hγ and the Hα/Hβ Balmer ratios using standard extinction law (Fitzpatrick, 1999) Table 1 lists the corresponding A_V and the associated error bars. Relative errors due to S/N and data analysis methodology have then been quadratically added, and hence the final error bars correspond to more than a 1σ error. The extinction factor of LIRGs averages to $A_V \sim 2.8$ at z~0.7, a value much larger than A_v=1.12 obtained by Kennicutt (1992) for normal spiral galaxies or A_V=0.57 derived by Gallagher et al. (1989) for irregular galaxies. Figure 2 shows the excellent correlation between extinction estimates from the Hβ/Hγ and the Hα/Hβ ratios. SFR were calculated using extinction corrected Hα line (Hβ in the case of galaxy 03.0495) integrated flux following the recipes of Kennicutt (1998). The correlation displayed in Figure 2a is valid over a wide range in redshift and luminosity. We give in this paper the cleanest evaluation of SFR of starbursts and LIRGS done up to now on the basis of Balmer lines. Having reached the limits of the method, we evaluate the validity of its application for ascertaining actual SFRs in dusty galaxies.

5. SFR derived from multi-wavelength correlations

A major fraction of the ionising photons related to star formation were reprocessed by dust in dust-enshrouded galaxies such as the LIRGs studied here. The IR luminosity (8–1000 μm) may also provide a good estimate of the SFR. We estimated the SFR using a set of SED template
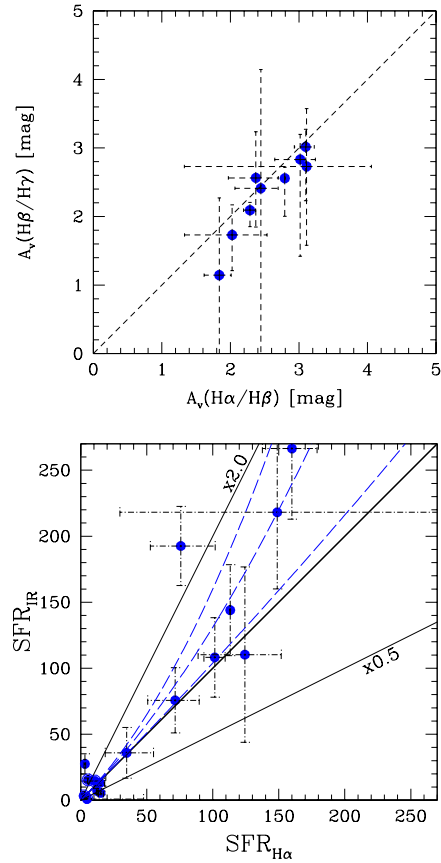

Fig. 2. (a) *Upper panel:* This plot shows the strong correlation that exists between the extinction estimated using the two differents Balmer ratios (Hβ/Hγ and Hα/Hβ). (b) *Bottom panel:* Comparison of the two SFRs, using MIR luminosities and Balmer emission line luminosities. Full line represents SFR$_{IR}$=(2-1-0.5) $\times$ SFR$H\alpha$. The dashed-line represents a polynomial (best) fit to the points (SFR$_{IR}$= SFR$_{H\alpha}\times$(1+a$\times$SFR$_{H\alpha}$), where a=3.11$^{6.0}_{0.4}$ $\times$ 10^{-3}). SFR$_{H\alpha}$ underestimates the global SFR for values larger than ~100M$_\odot$/yr.

from the STARDUST II model (Chanial et al, in prep) and the relationship found by Elbaz et al. (2002) between the MIR and the IR luminosity. For a few objects detected at radio wavelengths we have also derived the IR luminosity from the radio-FIR correlation (see Condon, 1992). All three methods produce results consistent within the error bars which are dominated by the uncertainties in the MIR photometry and the scatter of MIR (or radio)-IR relationship. SFR has been computed assuming the recipe of Kennicutt (1998), and allowing a direct comparison with our derivation of the SFR from Balmer emission lines, since both calculations assumed a Salpeter (1995) IMF with mass limits from 0.1 to 100$M_\odot$.

6. Discussion and conclusions

Extinction effects potentially affect a large cosmological sources and their consequences have been the subject of a

Table 1. Extinctions and SFR of distant LIRGs and nearby galaxies d etected by ISO(see enclosed jpg).

long debate in observational cosmology. In this letter, we study a representative sample of dust enshrouded starbursts, which, at moderate redshifts, can be extensively studied in spectroscopy, at MIR and at radio wavelengths. We have compared the instantaneous SFR related to the optical nebular emission ($SFR_{H\alpha}$) to the SFR estimated from the MIR emission measured by ISO , and, when available, from the radio emission These two methods give compatible results, and we denote the result by (SFR_{IR}). $H\alpha$ luminosities have been properly corrected for:(1) extinction corrections (using Balmer decrement ratio); (2) absorption line contamination (using moderate resolution spectroscopy) and (3) aperture correction (using photometric measurements). The latter correction could potentially lead to major errors. Indeed it assumes that the fraction of the emission line light which is sampled by the slit equals that of the continuum light derived from broad band photometry, which could be wrong. However, our extinction estimate from the $H\beta/H\gamma$ ratio does not depend on such assumption and agrees well with our estimate from the $H\alpha/H\beta$ ratio. Moreover, for the 8 distant galaxies, the aperture correction is generally close to 1, and so we believe that uncertainties related to aperture correction are marginal. IR luminosities have been estimated by (1) using the correlation between MIR and far-IR luminosities and (2) using the correlation between radio and far-IR luminosities. A good agreement is found using the two methods. Despite the large error bars on individual SFRs, we find a remarquable trend in the relationship between the two SFR estimates: (1) For starbursts with SFR_{IR} below $90 - 130 M_{\odot}/yr$, SFR estimates based on $H\alpha$ luminosities, properly corrected, agree well with SFR_{IR}, in agreement with analyses of local galaxies with low SFRs (Buat et al., 2002, Rosa-Gonzalez et al., 2002); (2) At larger IR luminosities, $H\alpha$ emission lines underestimate the SFR by factors up to 2.5 at $SFR_{IR}=250 M_{\odot}/yr$. (3) few objects show properties strongly discrepant from the empirical relationship between $SFR_{H\alpha}$ and SFR_{IR} which could be due to their individual star formation history: for example, if the star formation was rapidly decreasing (increasing), one would expect SFR_{IR} larger (smaller) than $SFR_{H\alpha}$. Our result is in excellent agreement with the recent study of the IRAS sources detected by the SDSS (Hopkins et al, 2003, see their Fig 15) in the local universe. However it substantially differs from that of Franceschini et al (2003, hereafter F03), who have studied similar sources in the HDFS. Indeed in the F03's Fig. 8, IR and $H\alpha$ estimates of the SFR are almost similar for LIRGs and ULIRGs, while for most of the less luminous IR galaxies, infrared provide larger values of the SFRs. Although the above results are somewhat in contradiction with our and Hopkins et al studies, one has to understand the major reasons of such a discrepancy. F03's Table 5 displays extinction corrected SFR(Halpha) values for 11 objects. For 7 of them,

they have estimated dust extinction from the stellar continuum on the basis of the rest-frame V-K colors or on the comparison between $H\alpha$ and rest-frame 2800AA fluxes; it is generally believed that the continuum can only provide gross estimates of the gas extinction, because it is strongly affected by the various and complex star formation histories. For the 4 resting objects (HDFS25, 27, 53 and 55), the discrepancy might be related to the fact that F03 have not corrected $H\beta$ fluxes for underlying absorption, leading to a systematic underestimate of $H\beta$ emission flux. Moreover 2 of these objects (HDFS25, 55) present a low S/N for the $H\alpha$ line (see R00 Fig. 1).

Using both SFR's, we have estimated an empirical polynomial relationship $SFR_{IR} = SFR_{H\alpha} \times (A \times SFR_{H\alpha} + 1)$, where $A=3.11^{6.0}_{0.4} 10^{-3}$ (which fits at best the points in Figure 2b, weighted according to the error bars). Applying our empirical relationship to the L_{IR} estimated by Flores et al. (1999) on field galaxies, one can derive in principle the $H\alpha$ luminosity density corresponding to the IR luminosity density at $z \leq 1$ (note that this result is insensitive to a change of cosmological constants). It results that the $H\alpha$ star formation density corresponds to 83% to 89% of the IR star formation density, for the Flores et al. lower and upper limit, respectively. This suggest that galaxies which actually dominates the cosmic star formation density at $z \leq 1$ are not ULIRGs, but correspond to the much more abundant population of LIRGs and starbursts. For determining the SFR, MIR fluxes which can be measured rapidly by satellites (ISO, SIRTF) give, and at least for the intrinsically bright IR galaxies, more accurate estimates than cumbersome optical and NIR spectroscopy. However, the detailed spectra bring useful information on metal abundances and on the evolutionary history of the galaxies, as we will show in subsequent papers.

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